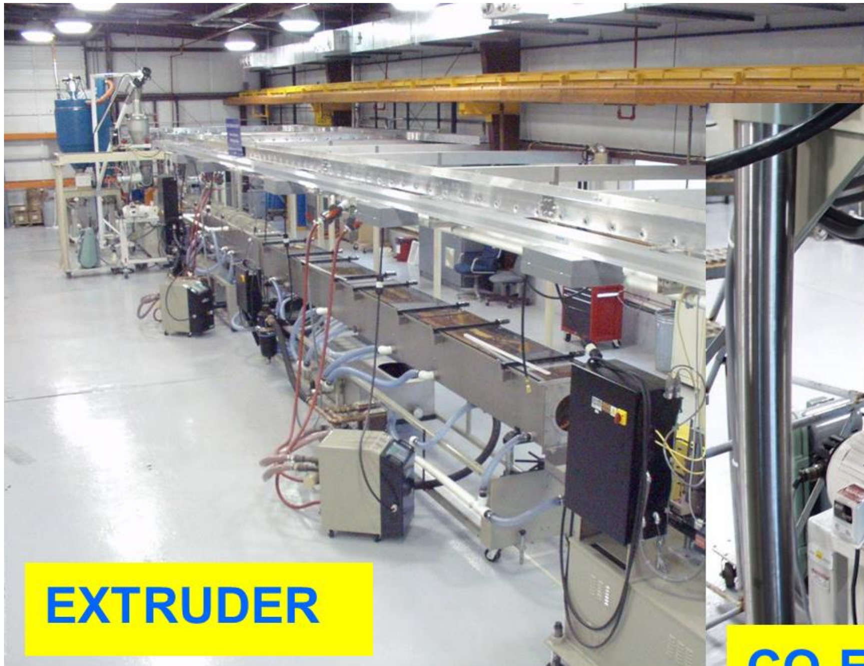
Update on Scintillator at Fermilab

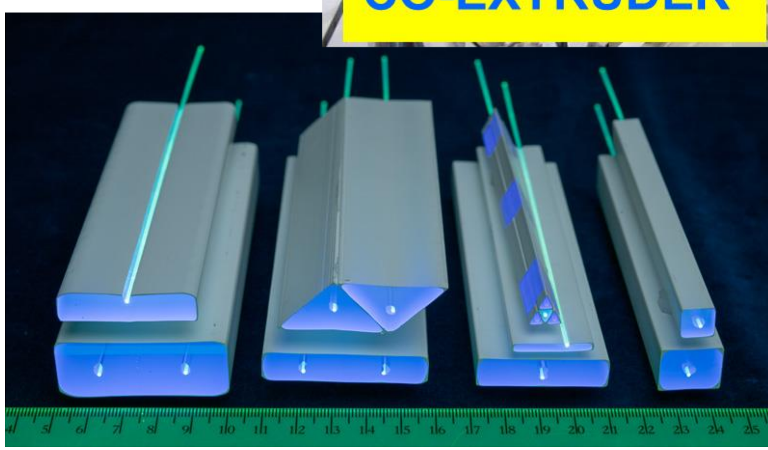
Jim Freeman, Alan Bross, Anna Pla-Dalmau

CPAD 2021

Mar 19, 2021

FNAL-NICADD Extrusion Line Facility





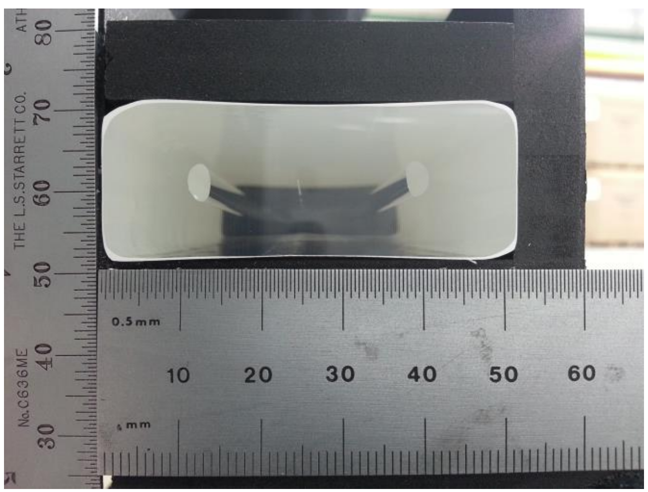
Product is extruded scintillator with integrated fiber holes, white reflective cladding

Fermilab extrusion Past/present fabrication

- FNAL experiments:
  - MINOS (supervision & QC)
  - MINERvA
  - Mu2e CRV – 2018
  - CMS -- 2021
  - LDMX – 2021
- Large projects:
  - K2K (Supervision & QC)
  - T2K: P0D, ECal, INGRID
  - DoubleCHOOZ
  - Pierre Auger: CNEA
  - Pierre Auger: KIT 2015-21
  - ICECUBE
  - INO – CMVD - 2019
- Small projects:
  - CANFRANC – Spain
  - INFN: Bologna, Brescia, Gran Sasso, Napoli, Padova
  - Inst. Phys. Globe - France
  - NYU – Abu Dhabi
  - Tel Aviv University
  - UIS – Colombia
  - Univ. Liverpool
  - IDEON – Canada – 2021
- DOE complex:
  - ANL: STAR (Supervision & QC)
  - JLAB: CLAS, CDet
  - LANL

PLASTIC SCINTILLATORS – Mu2e CRV PRODUCTION

2018
~ 26,000 Kg

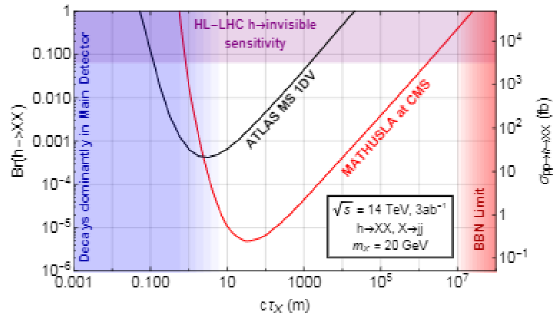


52 mm x 20 mm – 2 H – with TiO_2 coating

Fermilab

MATHUSLA. Baseline → Extruded scintillator/WLS/SIPM

- Long Lived Particles (LLP) natural in many BSM scenarios
  - singlet scalars mixing with SM Higgs, meta-stable Higgsinos, heavy neutral leptons, dark sectors, DM mediators…
- ATLAS, CMS & LHCb have a rich program of LLP searches
  - However, limited by the trigger, collision (& other) backgrounds & simply the size of the detector



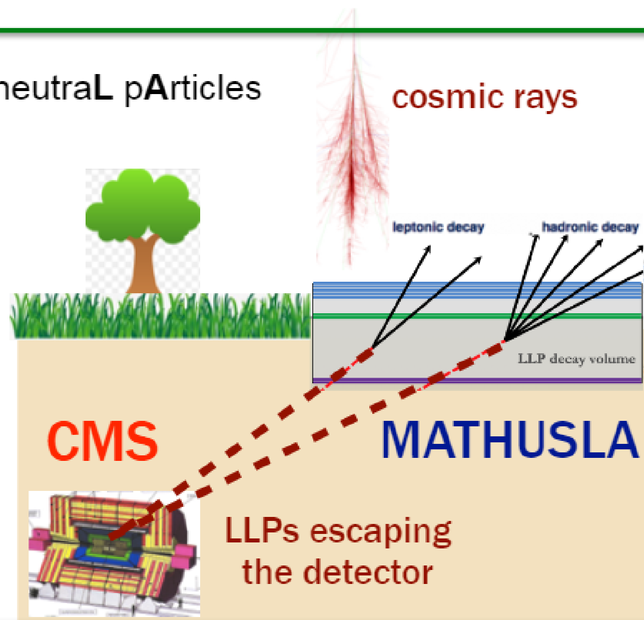
MATHUSLA = **MA**sive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles

- To be installed at the ground level above the CMS detector

✓ Near-zero backgrounds

✓ Sensitivity to lifetimes up to the BBN limit

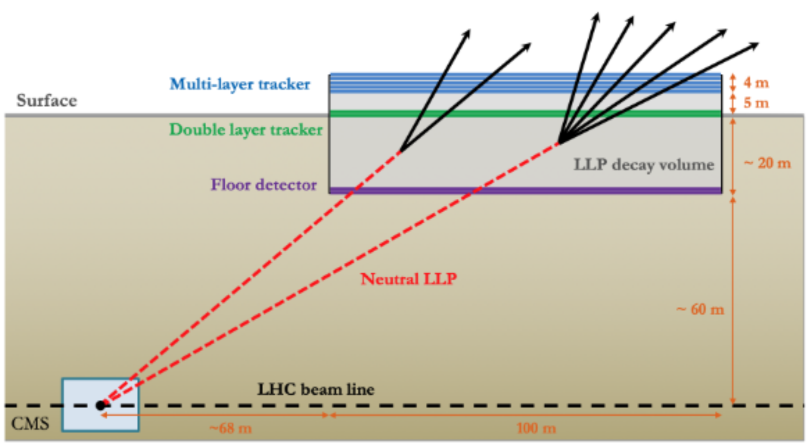
✓ Measurements of cosmic ray showers - guaranteed physics return

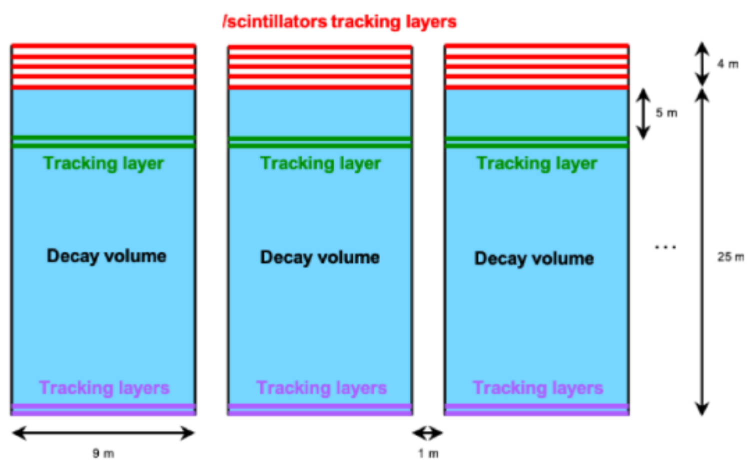


L. Morvaj Physics Beyond Colliders CERN 2021

MATHUSLA. Baseline → Extruded scintillator/WLS/SIPM

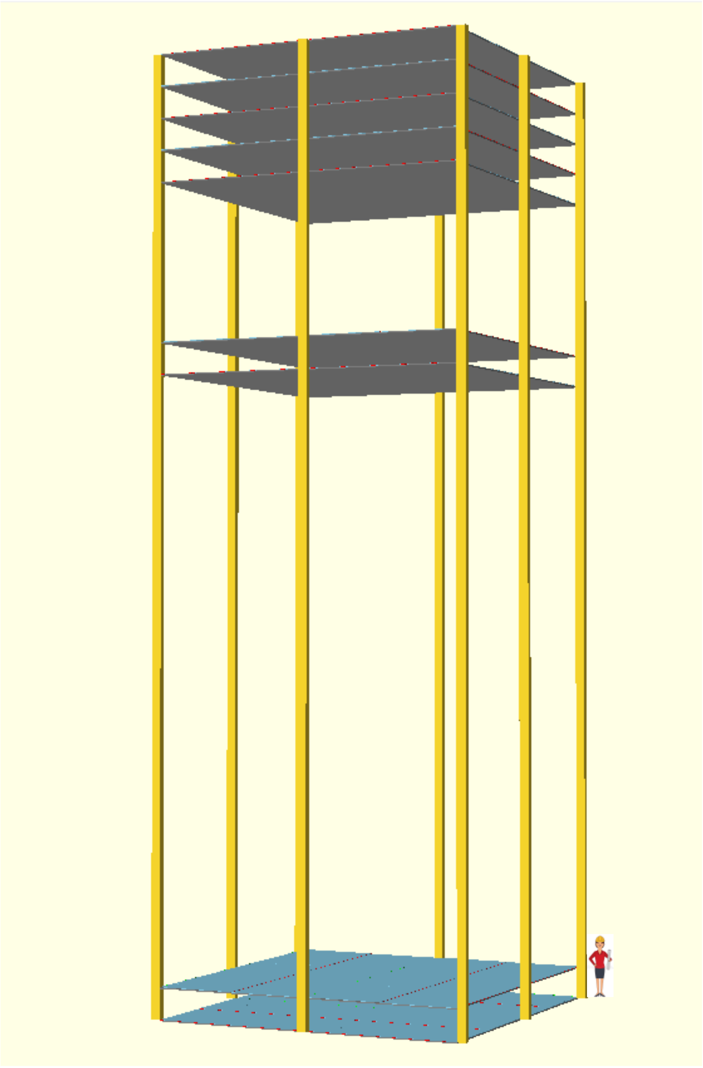
- Decay volume: 100 m x 100 m x 25 m
- Modular design:
  - 9m x 9m units (x 100)
  - each unit 9 layers of scintillating-detector planes for position and timing (5 top, 2 middle near top, 2 floor)
- Floor layer: reject charged particles from the LHC and cosmic muon backscattering

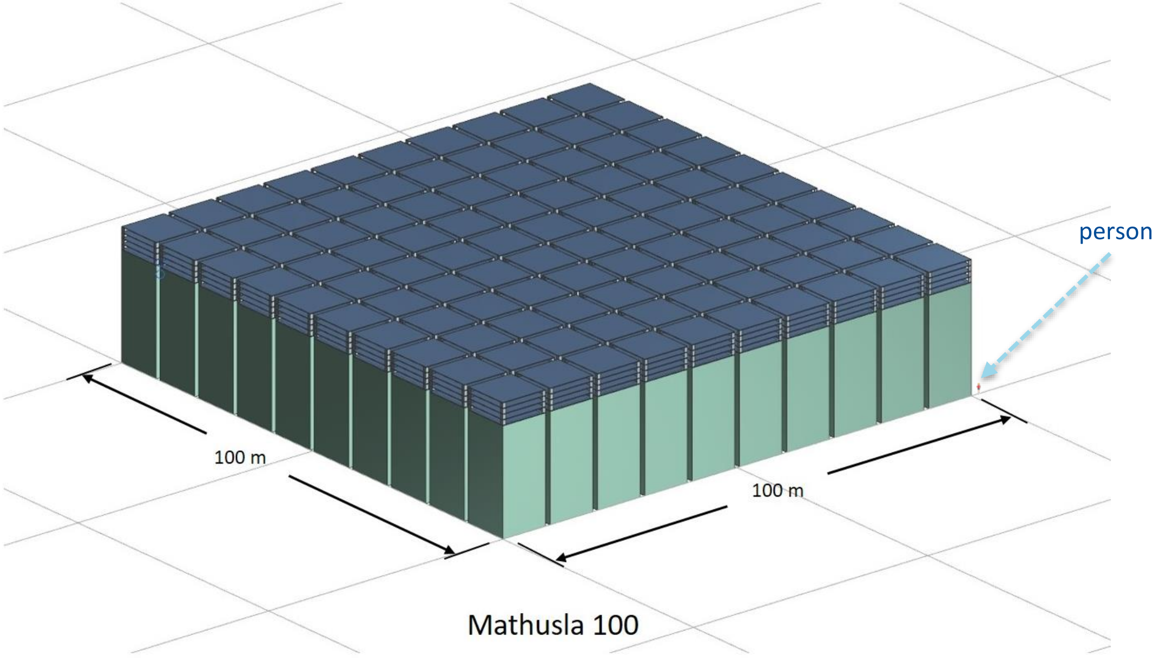




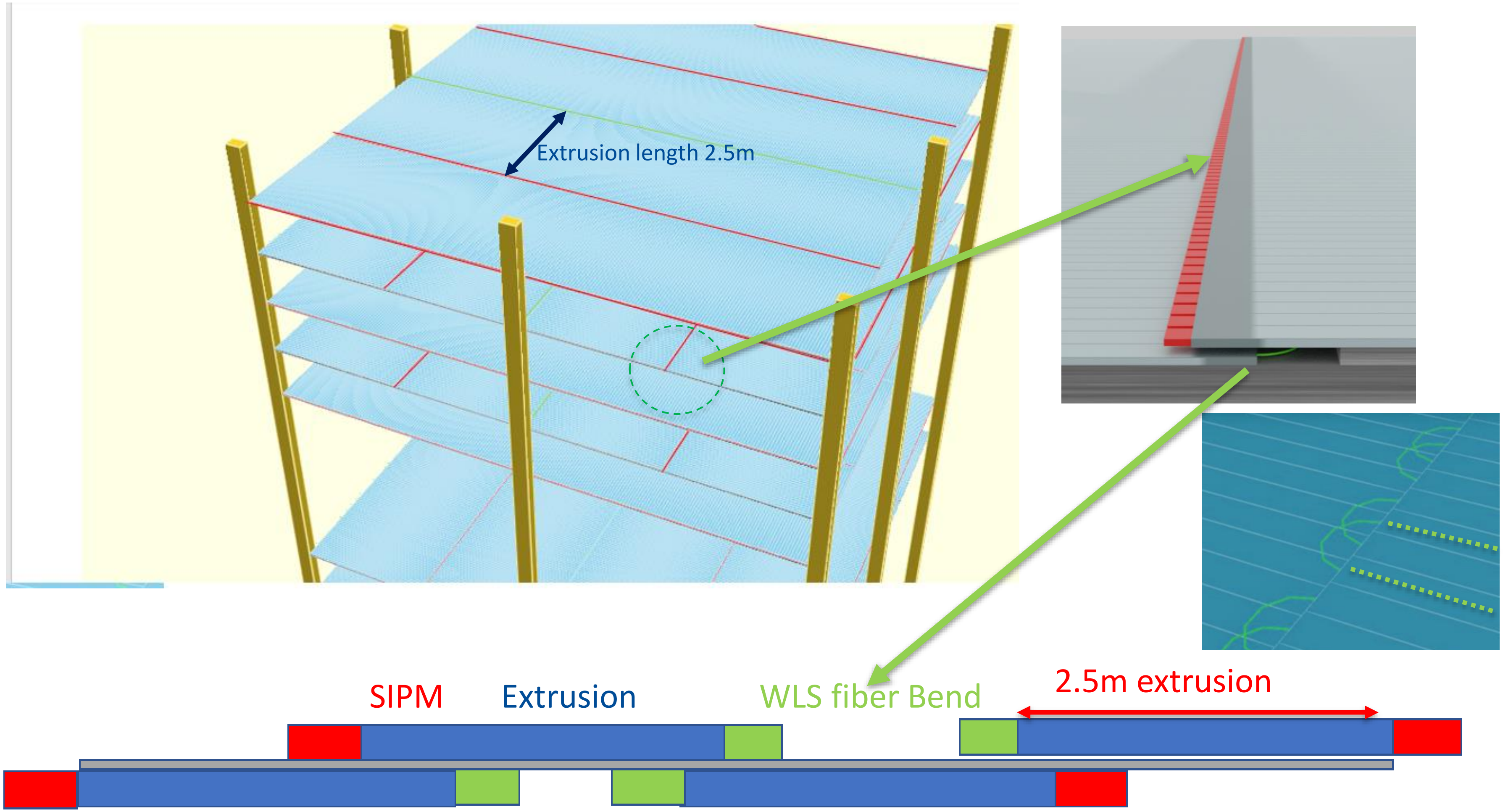
L. Morvaj PBC 2021

Mathusla Module, 100 module detector





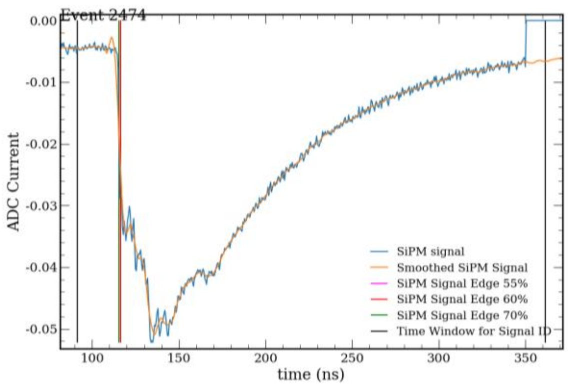
MATHUSLA: Detail of scintillator extrusions forming layer

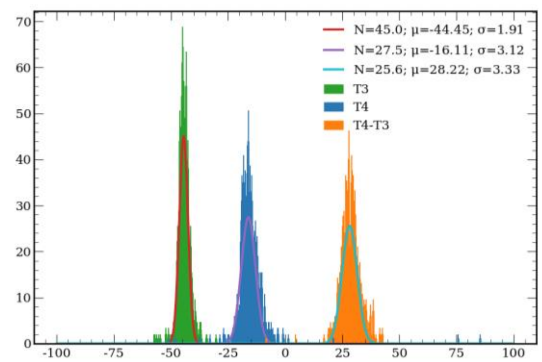


MATHUSLA extrusion design under study. Here 2.5m extrusion, 1.5mm diameter WLS fiber looped back even/odd extrusions. ~5.2m fiber

MATHUSLA Issues

- Timing resolution. ~1ns rms timing for MIP is desired.
  - Simulations to understand contributions
  - Testbeam/cosmics



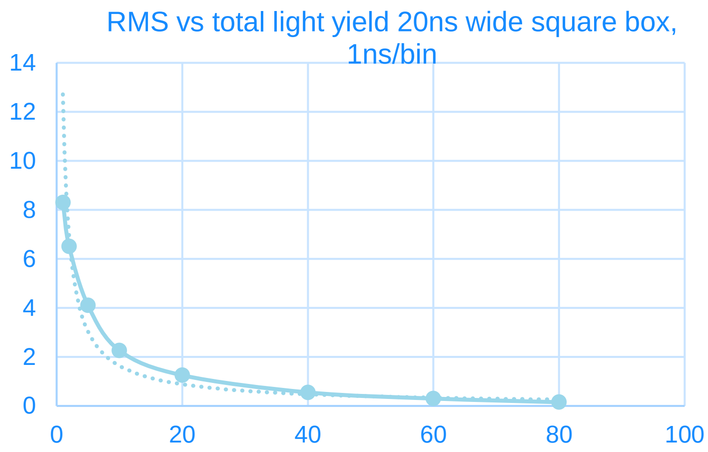


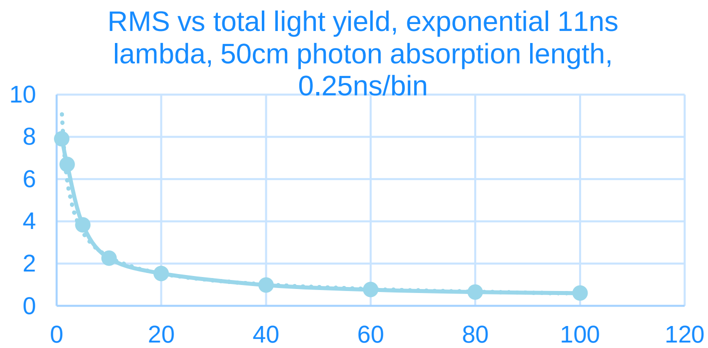
Cosmic data. Extrusion with 5.2meter fiber, SIPMs 2Gss with Savgol smoothing, constant fraction discriminator simulation. Keane Tan, U Rochester 3/21

- Mathusla will use about 1000t of scintillator. Cost is critical.
  - With very large production, reduce cost by
    - Industrialization?
    - Robotics to reduce labor?

Generic Simulations of Extrusion/fiber/SIPM

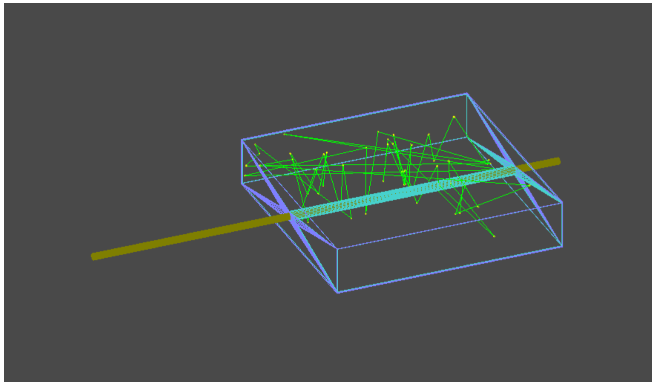
Parametric simulation





System simulations in progress. Tuning GEANT on previous measurements. Study tunable parameters of extrusion/WLS system:

- Photon absorption length in extrusion
- Reflective surface
- Extrusion shape, location of fibers
- WLS decay time
- Optical fiber dispersion
- Overall Light yield



Geant4

Yihui Lai UMD

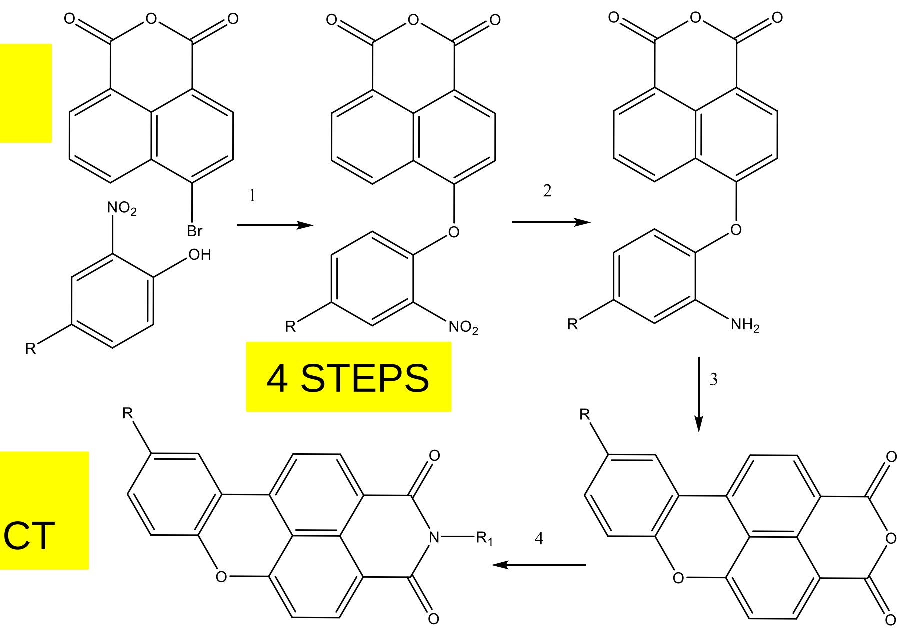
Improving light yield of extrusion. Cladding/reflectivity.

20 cm long extrusion (1X4cm) threaded with 1.5mm dia / 5.2m long fiber into SIPMs. Measure total light yield for cosmics. → cladding has profound effect on light yield. Preparing optics simulation to explore.

Date	Sample Name	Total Light Yield (pe)
Feb 22	Default white clad 20cm	42
Feb 11	Black foil, 20cm	10.5
Feb 15	Tyvek 20cm	40.2
Feb 24	Tyvek 20cm 2nd measurement	40.1
Feb 25	ESR 20cm	58.2

SCINTILLATOR R&D: Brighter faster wavelength shifter fluor: Synthesis of K27

STARTING MATERIALS



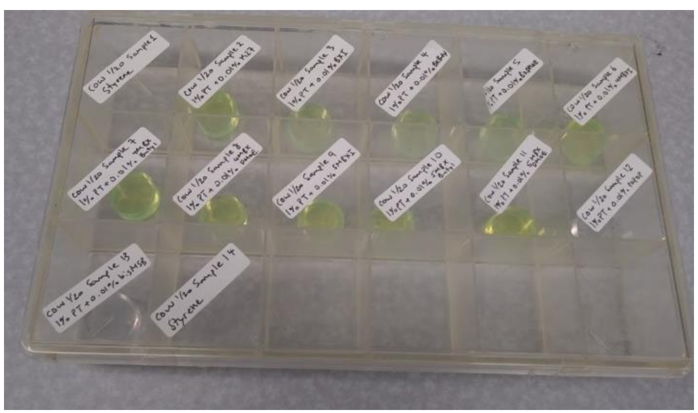
FINAL PRODUCT

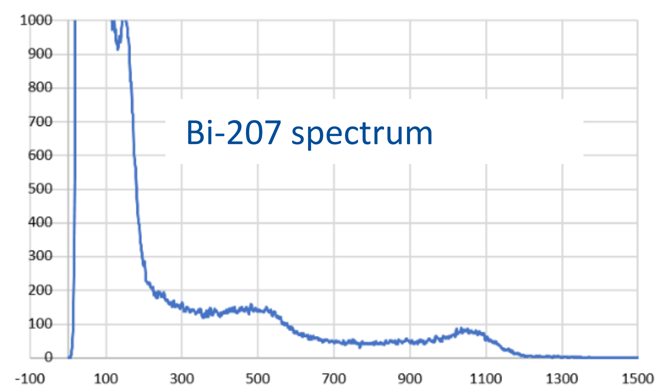
- 4 step synthesis
- Make variants to find brighter/faster materials
- Light yield measurements complete
- Decay time measurements ongoing

SCINTILLATOR R&D: LIGHT YIELD

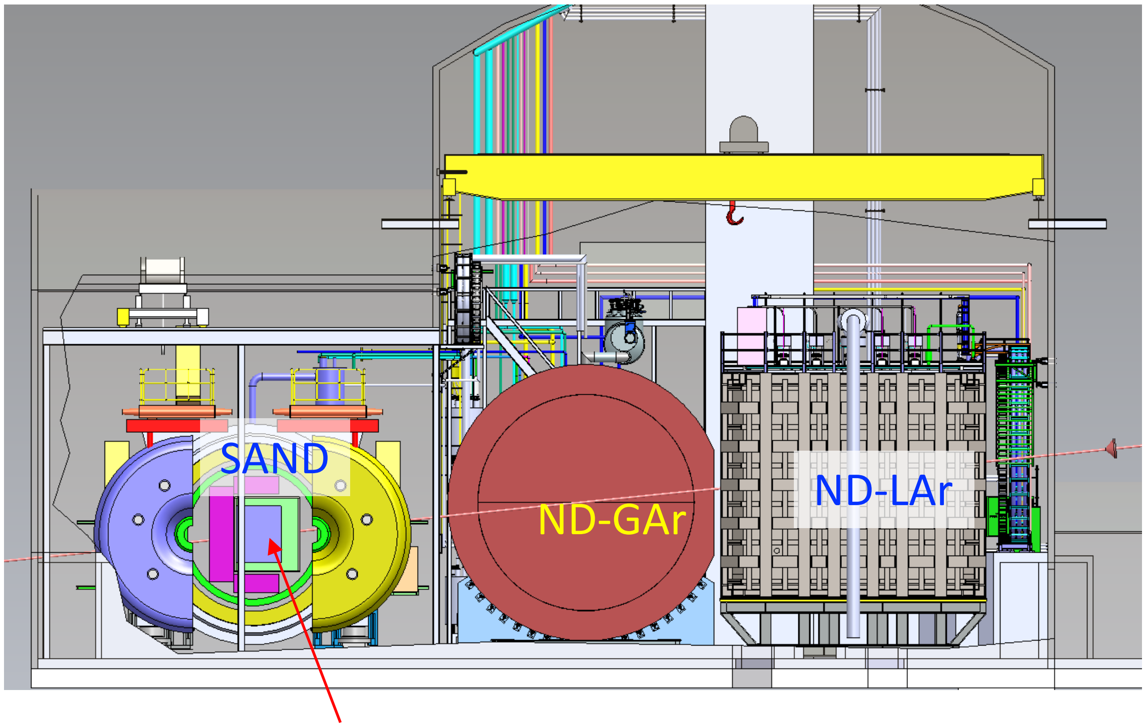
PULSE HEIGHT MEASUREMENTS USING Bi-207					
SAMPLE	**emission**	**PED.**	**MAX.**	**DELTA**	**RATIO***
1% PT + 0.01% K27	green	23	963	940	1
1% PT + 0.01% BXI	green	22	1045	1023	1.09
1% PT + 0.01% BXButyl	green	22	899	877	0.93
1% PT + 0.01% BXDMOE	green	25	433	408	0.43
1% PT + 0.01% 4MBXI	green	22	805	783	0.83
1% PT + 0.01% 4MBXButyl	green	20	1019	999	1.06
1% PT + 0.01% 4MBXDMOE	green	20	879	859	0.91
1% PT + 0.01% 5MBXI	green	22	1077	1055	1.12
1% PT + 0.01% 5MBXButyl	green	22	1012	990	1.05
1% PT + 0.01% 5MBXDMOE	green	20	1066	1046	1.11
1% PT + 0.01% POPOP	blue	21	1079	1058	1.13
1% PT + 0.01% bisMSB	blue	19	1003	984	1.05

*not corrected for PMT efficiency





3DST as part of DUNE near detector complex

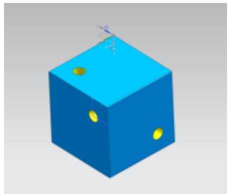


3DST active target

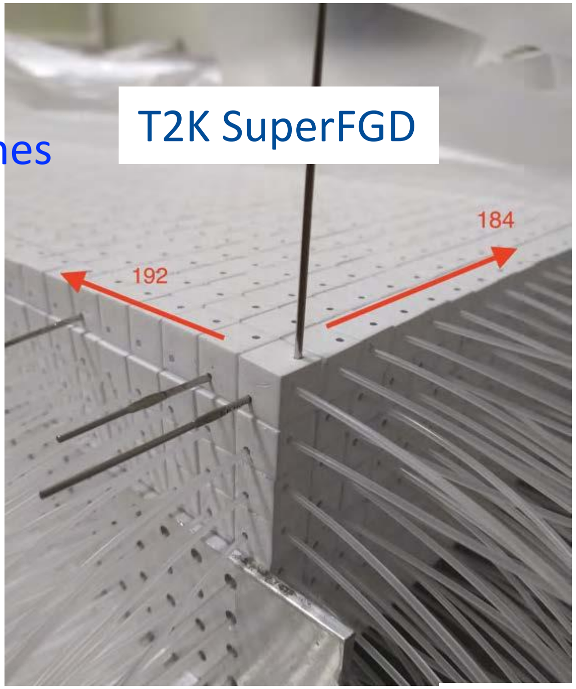
- The DUNE near detector complex consists of 3 components
  - Pixelated readout LAr: ND-LAr
  - High-pressure (10 bar) gas TPC system: ND-GAr
  - System for on Axis Neutrino Detection: SAND (beam monitor)
    - The 3DST is one option for the active target of SAND

3DST – injection molding "voxels"

3-Dimensional Scintillator Tracker: 3DST

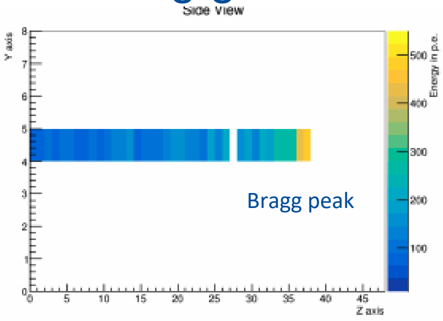


And repeat **many many** times



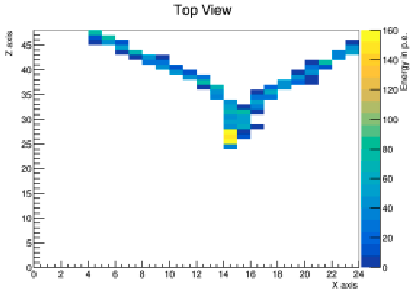
- SuperFGD basic element 1 cm cube of plastic scintillator
- Light collected by 3 orthogonal WLS fibers
- Cubes have TiO_2 coating
  - Optical isolation
- Readout: SiPMs
- Timing gives event T_0

- Extensive R&D for T2K ND280 upgrade.
- The DUNE 3DST is ~ 4X larger than the T2K Super FGD
  - 2.4 x 2.4 x 2 m^3
  - ~3.4 million cubes
- Holes have been drilled up to now
  - Problems with drill "drift" which makes threading WLS fiber more difficult
  - Injection mold with holes much more precise dimensionally
- New capability at FNAL.
- Goal: Co-mold voxel+holes+coating



Stopping proton
CERN testbeam

gamma conversion
(from ND280 TDR)



Injection Molding for High Granularity Detectors

Injection-molded scintillator is cost-effective way to make new generation fine grained detectors. (CMS HGC Scintillator section uses ~0.25M tiles; DUNE 3DST 3M cubes) Concept is to build DUNE 3DST with injection molded tiles (voxels) where all voxel processing is done during injection molding: holes, opaque white coating. Goal is to develop a small scale prototype using in-house molded voxels

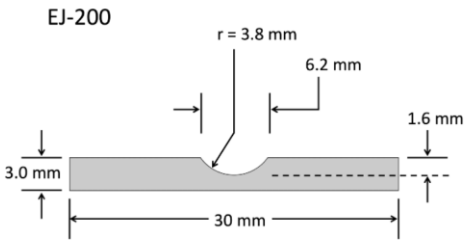
Injection molding machine at Lab 5 will be used to make the voxels.

Advantages over machined tiles:

- Cost
- Precision: Each voxel will be identical. Ease "threading" of WLS fibers…
- Uniformity: Coatings will be built-in, reduced variation
- Quality: No machined surfaces or holes so improved optical quality
- Production time: Can produce many per minute

Injection molded vs cast scintillator light yield

2020 Fermilab FTBF testbeam, 120 GeV proton “MIPs”. Fit to modified Landau, MPV. Comparison of “SIPM-on-tile” geometry 30x30mm x3mm tiles. Tiles wrapped in Vikuiti 3M ESR foil



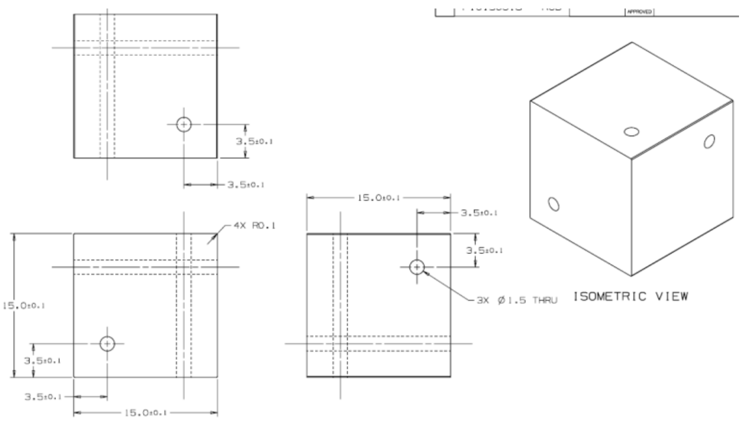
Sample Name	Total Light Yield (pe)
Cast Eljen EJ200	33.9+-1.0
Cast Eljen EJ208	34.8+-1.0
Cast Eljen EJ262	33.0+-1.0
injection molded sample 1	23.4+-0.7
injection molded sample 2	23.7+-0.7

Conclude scintillator cast has 1.5X light yield of Injection-molded. Want to improve injection molded material. Study improvements in:

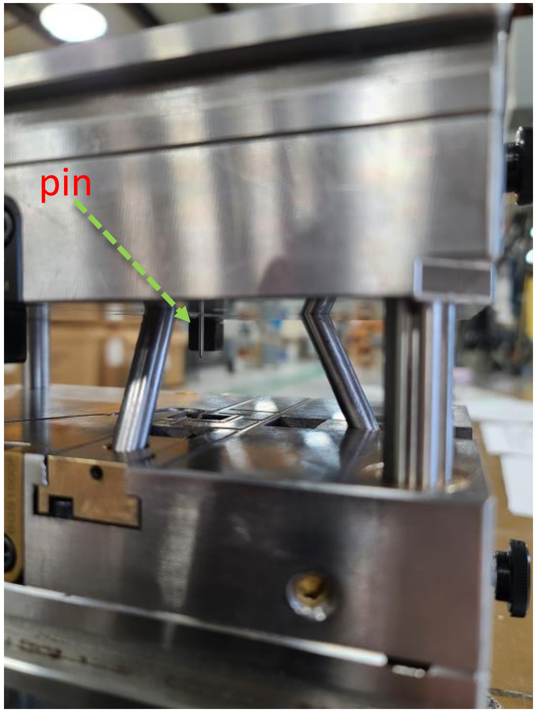
- Materials
- Chemistry
- Process

Injection Molding Plans for Voxel

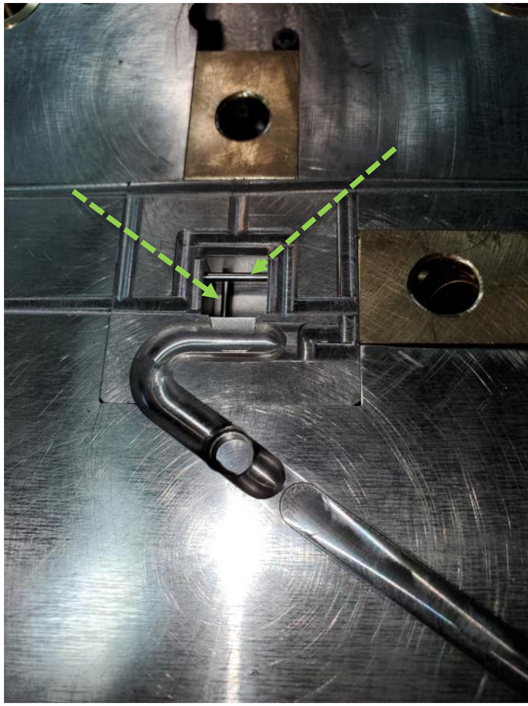
- Working to understand limitations of injection molded scint light yield
- Create scintillator pellets for injection molder.
- Mold fabricated, preparing to install on machine.
- Next step to produce cubes with 3 orthogonal holes
- Final step adding reflective cladding as an integrated process



Mold for Voxel, at Fermilab Lab 5



Mold open



Mold closed, top removed

Summary

- Scintillator continues to be very important tool for detector design
- Important to keep improving process
  - More light yield
  - Faster materials
  - New methods such as co-molded cladding and through holes
  - New methods for reducing cost/improving material